High-Energy Neutrinos Produced by Interactions of Relativistic Protons in Shocked Pulsar Winds

S. Nagataki
Yukawa Institute for Theoretical Physics, Kyoto University, Oiwake-cho Kitashirakawa Sakyo-ku, Kyoto 606-8502, Japan

We have estimated fluxes of neutrinos and gamma-rays that are generated from decays of charged and neutral pions from a pulsar surrounded by supernova ejecta in our galaxy, including an effect that has not been taken into consideration, that is, interactions between high energy cosmic rays themselves in the nebula flow, assuming that hadronic components are the energetically dominant species in the pulsar wind. Bulk flow is assumed to be randomized by passing through the termination shock and energy distribution functions of protons and electrons behind the termination shock are assumed to obey the relativistic Maxwellians. We have found that fluxes of neutrinos and gamma-rays depend very sensitively on the wind luminosity, which is assumed to be comparable to the spin-down luminosity. In the case where $B = 10^{12}$G and $P = 1$ms, neutrinos should be detected by km^3 high-energy neutrino detectors such as AMANDA and IceCube. Also, gamma-rays should be detected by Cherenkov telescopes such as CANGAROO and H.E.S.S. as well as by gamma-ray satellites such as GLAST. On the other hand, in the case where $B = 10^{12}$G and $P = 5$ms, fluxes of neutrinos and gamma-rays will be too low to be detected even by the next-generation detectors.

1. Introduction

It has been about 35 years since Goldreich and Julian (1969) pointed out that a rotating magnetic neutron star generates huge electric potential differences between different parts of its surface and, as a result, should be surrounded with charged plasma, which is called a magnetosphere. Gunn and Ostriker (1969) also pointed out the possibility that a rotating magnetic neutron star may be a source of high energy cosmic rays. Such high energy cosmic rays are considered to be driven along magnetic field lines since these lines do not cross. Also, since part of the magnetic fields around the neutron star passes through the light cylinder, which means such magnetic fields are open, accelerated charged particles are driven to outside of the light cylinder, which are called as pulsar winds. The pulsar winds are usually considered to be composed of electron-positron pairs since electron-positron pairs will be created so as to eliminate electric fields that are parallel to magnetic fields at a region where net charge density is not equal to the Goldreich-Julian density. However, it is also pointed out that hadronic component may exist in pulsar winds as a consequence of the net charge neutrality in the outflow. Moreover, it is pointed out that hadronic components may be the energetically dominant species although they are dominated by electron-positron pairs in number. This is because inertial masses of hadrons are much larger than that of electron.

Based on the assumption that hadronic components are not negligible in pulsar winds, some scenarios are proposed to produce high energy neutrinos and gamma-rays from decays of charged and neutral pions that are produced by interactions between hadronic, accelerated high energy cosmic rays and surrounding photon fields and/or matter. Atoyan and Aharonian (1996) estimated flux of gamma-rays and discussed its contribution on the observed spectrum of the Crab nebula, although they concluded that its contribution may be important only at energies above 10 TeV. Bednarek and Protheroe (1997) proposed that accelerated heavy nuclei can be photo-disintegrated in the pulsar's outer gap, injecting energetic neutrons which decay into protons. The protons from neutron decay inside the supernova ejecta should accumulate, producing neutrinos and gamma-rays in collisions with the matter in the supernova ejecta. There are some papers based on this scenario and flux of neutrinos and/or gamma-rays is estimated. Beal and Bednarek (2002) proposed that accelerated cosmic rays will interact with the photon fields inside the supernova remnant at the very early phase (within $\sim$1 yr) of a supernova explosion. Bednarek (2001) calculated the extragalactic neutrino background based on this scenario.

In this study, we estimate fluxes of neutrinos and gamma-rays including an effect that has not been taken into consideration, that is, interactions between high energy cosmic rays themselves. This picture is based on the works given by Rees and Gunn (1974) and Kennel and Coroniti (1984). Rees and Gunn (1974) pointed out that the supersonic pulsar wind would terminate in a standing reverse shock located at a distance r_s from the pulsar. Beyond the termination shock, the highly relativistic, supersonic flow is randomized and bulk speed becomes subsonic, obeying the Rankine-Hugoniot relations. According to Hoshino et al. (1992), who studied the theoretical properties of relativistic, transverse, magnetosonic collisionless shock waves in electron-positron-heavy ion plasmas, proton distribution functions in the down stream are found to be almost exactly described by relativistic Maxwellians with temperatures

$T_{p,2}/\gamma_1 m_p c^2 \sim 0.34$, where $T_{p,2}$ is temperature at the down stream, γ_1 is the bulk Lorenz factor of protons in the up stream. It is noted that protons are not thermalized through the interactions with protons themselves, and/or electrons but just obeys the Maxwellian distribution through transferring cyclotron waves. This subsonic flow speed would be, by communicating with the nebula boundary at r_N via sound waves, adjusted to match the expansion speed of the supernova remnant (that is, supernova ejecta) at the innermost region. This subsonic flow is called as nebula flow in the study of Kennel and Coroniti (1984). We also adopt this definition in this study. In this study, we calculate flux of neutrinos and gamma-rays from charged and neutral pion decays in the nebula flow which are produced through the interactions between high energy protons themselves, assuming that energy distribution functions of protons obey the relativistic Maxwellians.

In this study, as the previous works, we assume that protons are energetically dominant in the pulsar winds. Thus, we describe the nebula flow using the proton mass as a unit of mass. We estimate pion production rates due to the interactions between high energy protons using proper Lorenz transformations. As for the cross sections between protons, scaling model is adopted. Isobar model is not included in this study since we consider production rates of high energy pions. Calculating the spectrum of neutrinos and gamma-rays in the termination shock rest frame, we estimate these fluxes at the earth assuming that the pulsar is located at 10 kpc away from the earth.

2. Method of Calculation

2.1. Nebular Flow

As stated in section 1, we adopt the model presented by Kennel and Coroniti (1984), assuming that protons are energetically dominant. In their model, the pulsar's spin down luminosity L just ahead of the shock is divided between particle and magnetic luminosity as follows:

$$L = 4\pi n \gamma r_s^2 m_p c^3 (1+\sigma), \tag{1}$$

where n is the proper density of proton, u is the radial four speed of the flow, $\gamma^2 = 1 + u^2$, r_s is the radial distance of the shock from the pulsar, m_p is the proton mass, c is the speed of light, $sigma$ is the ratio of the magnetic plus electric energy flux to the particle energy flux,

$$\sigma = \frac{B^2}{4\pi n u \gamma m_p c^2}, \tag{2}$$

and B is the observer frame magnetic field. The maximum energy of the protons just ahead of the shock is estimated by the potential difference between the equatorial plane and pole of the rotating neutron star.

$$m_p c^2 \gamma_{\max} = 3 \times 10^{12} R_6 B_{12}/P^2 \quad \mathrm{eV}, \tag{3}$$

where R_6 is the radius of the neutron star in 10^6 cm, B_{12} is the amplitude of the magnetic field at pole of the neutron star, and P is the period of rotation of the pulsar in second. We adopt $\gamma_{\max}$ for the bulk velocity of the pulsar wind in the upstream.

The upstream flow is connected to the downstream via the Rankine-Hugoniot relations for perpendicular shock. As for the downstream flow, the steady state equation of motion is adopted. Position of the termination shock is determined so as to achieve the pressure balance between the supernova remnant and downstream of the pulsar wind at the inner-edge of the supernova remnant. We estimate the pressure in the supernova remnant by assuming that the ratio of the thermal energy relative to the kinetic energy is about 0.02 in the supernova remnant. Total explosion energy of a supernova is taken to be 10^{51} erg. The velocity of the inner-edge of the supernova remnant is set to be 2000 km s^{-1}. As for the distribution of the protons in the downstream, the Maxwellian with the temperature that gives the required pressure at each position is adopted.

2.2. Emissivity of High Energy Gamma-rays and Neutrinos

Next, we calculate the emissivity of high-energy gamma-rays and neutrinos using the formulation as follows:

$$F(E_\pi) = 2\pi c \int R^2 dR \int_1^\gamma d\gamma_1 \int_\gamma^\infty \gamma_2$$
$$\int_{-1}^{1} d\cos\theta \frac{d\sigma(\gamma_1, \gamma_2, \cos\theta)}{dE_\pi} n(R,\gamma_1) n(R,\gamma_2)$$
$$\times \sqrt{(\vec{\beta_1} - \vec{\beta_2})^2 - (\vec{\beta_1} \times \vec{\beta_2})^2}, \tag{4}$$

where γ_1, γ_2 are the respective Lorenz factors of the two protons, $\cos\theta = \vec{\beta_1} \cdot \vec{\beta_2} / \left|\vec{\beta_1}\right| \left|\vec{\beta_2}\right|$, R is the radius with respect to the neutron star, $n(R,\gamma)$ is the differential number density of protons at position R, and $d\sigma(\gamma_1, \gamma_2, \cos\theta)/dE_\pi$ is the differential cross section of proton-proton interaction.

The energy spectrum of gamma-rays produced through the decays of neutral pions in the fluid-rest frame is obtained as

$$F(E_\gamma) = 2 \int_{E_{\pi,\min}}^{\infty} dE_\pi \frac{F(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2}}, \tag{5}$$

where $E_{\pi\,\min}$ is the minimum pion energy required to produce a gamma-ray with energy E_γ. In the observer's frame, the energy spectrum of photons are

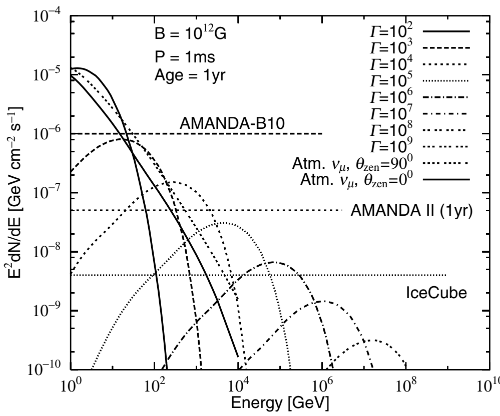

Figure 1: Spectrum of energy fluxes of neutrinos from a pulsar which is located 10 kpc away from the earth. The amplitude of the magnetic field and period of the pulsar is assumed to be 10^{12}G and 1ms. The minimum detectable energy flux of AMANDA-B10, AMANDA II (1yr), and IceCube is represented by horizontal lines. The atmospheric neutrino energy fluxes for a circular patch of 1° are also shown. The age of the pulsar is set to be 1yr.

expressed as

$$\frac{F'(E'_\gamma)}{d\Omega'} = \sum_{\Delta V} \frac{F(E_\gamma)}{\Gamma^2(1-\beta\cos\theta')}\frac{1}{4\pi}, \qquad (6)$$

where Γ is the bulk Lorenz factor of the fluid element at each position in the observer's frame, θ' is the angle between the line of sight and direction of the flow, and ΔV is the volume of the each fluid element. The dashes($'$) represent the quantum for the observer's frame. The flux of neutrinos and pions can be obtained as a result of pion decays. although $\mu^\pm \to e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$ is a 3-body process and slightly complicated. As for the differential cross section of pion production, we adopted the formulation presented by Badhwar et al. (1977).

3. Results

In figures 1 and 2, we show spectrum of energy fluxes of neutrinos from a pulsar which is located 10kpc away from the earth. The amplitude of the magnetic field and period of the pulsar is assumed to be 10^{12}G and 1ms. The detection limits of the energy flux for AMANDA-B10, AMANDA II (1yr), and IceCube are represented by horizontal lines. The atmospheric neutrino energy fluxes for a circular patch of 1° are also shown. Figure 1 represents the case that the age of the pulsar is 1yr, while Figure 2 represents the case that the age is 10^2yr. From this figure, we can find that there is a possibility to detect the signals of neutrinos from pulsar winds in our galaxy.

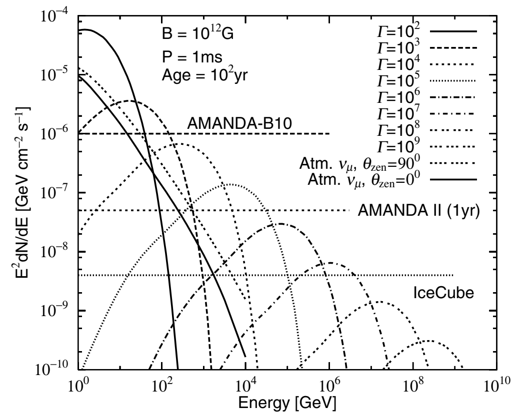

Figure 2: Same with Fig.1, but the age of the pulsar is set to be 10^2yr.

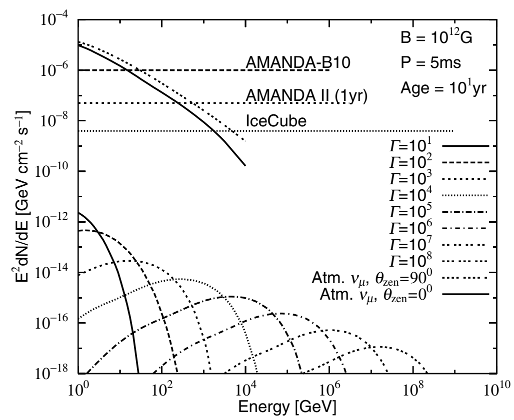

Figure 3: Same with Fig.1, but the age of the period of the pulsar is set to be 5ms.

For comparison, in figures 3 and 4, we show the spectrum of energy fluxes of neutrinos from a pulsar of which the amplitude of the magnetic field and period are assumed to be 10^{12}G and 5ms. Location of the pulsar is assumed to be 10 kpc away from the earth. Figure 3 represents the case that the age of the pulsar is 10yr, while Figure 4 represents the case that the age is 10^3yr. In these cases, the fluxes of neutrinos are much lower than the atmospheric neutrinos and detection limits of km^3 high-energy neutrino detectors. We can conclude that the detectability of the signals from the pulsar winds strongly depends on the period of the pulsar, which reflects the luminosity of the pulsar winds.

In figures 5 and 6, integrated gamma-ray fluxes from the neutral pion decays are shown assuming that the supernova ejecta has been optically thin for gamma-rays. The amplitude of the magnetic field and period of the pulsar are assumed to be 10^{12}G and 1ms. Figure 3 represents the case that the age of the pulsar is 1yr, while Figure 4 shows the case that the age of the

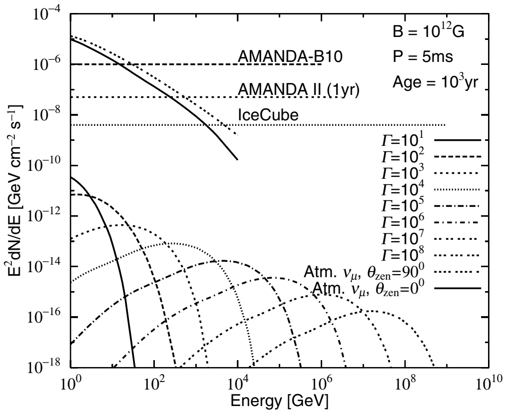

Figure 4: Same with Fig.2, but the age of the period of the pulsar is set to be 5ms.

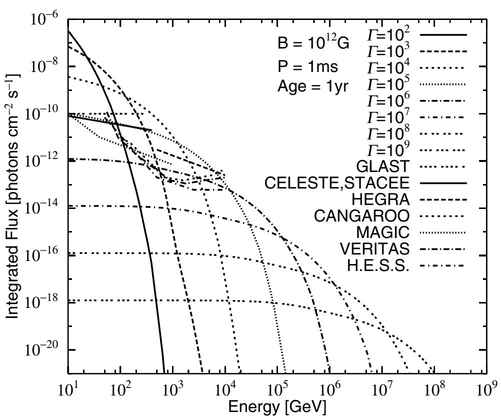

Figure 5: Integrated gamma-ray fluxes from the neutral pion decays are shown. The amplitude of the magnetic field and period of the pulsar are assumed to be 10^{12}G and 1ms. The age of the pulsar is set to be 1yr. The minimum detectable integrated fluxes of GLAST, STACEE, CELESTE, HEGRA, CANGAROO, MAGIC, VERITAS, and H.E.S.S. are also shown.

pulsar is 10^2 yr. The detection limits of integrated fluxes for GLAST, STACEE, CELESTE, HEGRA, CANGAROO, MAGIC, VERITAS, and H.E.S.S. are also shown. From these figures, we can find that there is a possibility to detect gamma-rays from decays of neutral pions by these telescopes.

On the other hand, we show the same figures in figures 7 and 8, but for the case that the period of the pulsar is 5ms. Figure 7 represents the case that the age of the pulsar is 10yr, while Figure 8 shows the case that the age of the pulsar is 10^3 yr. In these cases, the flux of gamma-rays is too low to detect.

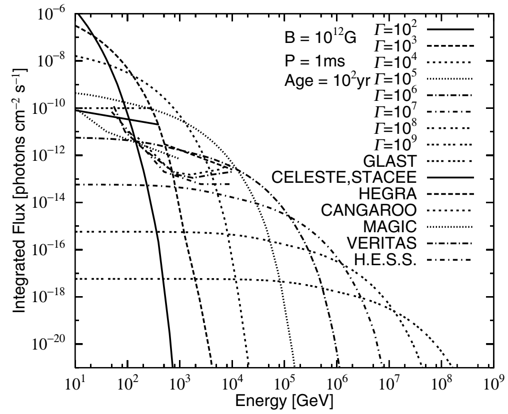

Figure 6: Same with Fig.5, but the age of the pulsar is set to be 10^2 yr.

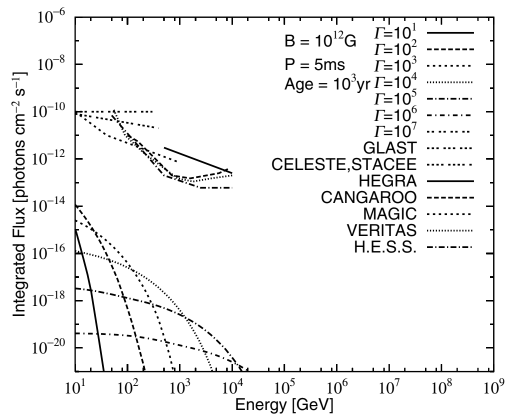

Figure 7: Same with Fig.5, but the period of the pulsar is set to be 5ms and the age of the pulsar is set to be 10yr.

4. Summary and Conclusion

In this study, we have estimated fluxes of neutrinos and gamma-rays that are generated from decays of charged and neutral pions from a pulsar surrounded by supernova ejecta in our galaxy, including an effect that has not been taken into consideration, that is, interactions between high energy cosmic rays themselves in the nebula flow, assuming that hadronic components be the energetically dominant species in the pulsar wind. Bulk flow is assumed to be randomized by passing through the termination shock and energy distribution functions of protons and electrons behind the termination shock obey the relativistic Maxwellians.

We have found that fluxes of neutrinos and gamma-rays depend very sensitively on the wind luminosity, which is assumed to be comparable with the spin-down luminosity. In the case where $B = 10^{12}$G and $P = 1$ms, neutrinos should be detected by km^3 high-energy neutrino detectors such as AMANDA

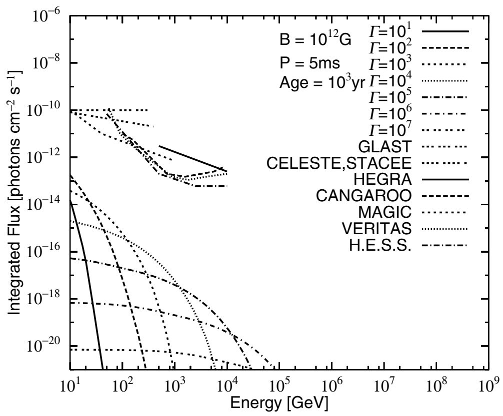

Figure 8: Same with Fig.7, but the age of the pulsar is set to be 10^3yr.

and IceCube. Also, gamma-rays should be detected by Cherenkov telescopes such as CANGAROO and H.E.S.S. as well as by gamma-ray satellites such as GLAST. On the other hand, in the case where $B = 10^{12}$G and $P = 5$ms, fluxes of neutrinos will be too low to be detected even by the next-generation detectors.

We have found that interactions between high energy cosmic rays themselves are so effective that this effect can be confirmed by future observations. Thus, we conclude that it is worth while investigating this effect further in the near future.

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